

Short Baseline ν Physics Experiments & Searches for Physics Beyond the 3 ν Paradigm

W.C. Louis, LANL

Intensity Frontier Workshop, November 30, 2011

- Neutrino Oscillations
- Tantalizing Short Baseline Results (Anomalies)
- Theoretical Interpretations
- Future Experiments for Addressing the Anomalies
- Conclusions

Probability of Neutrino Oscillations

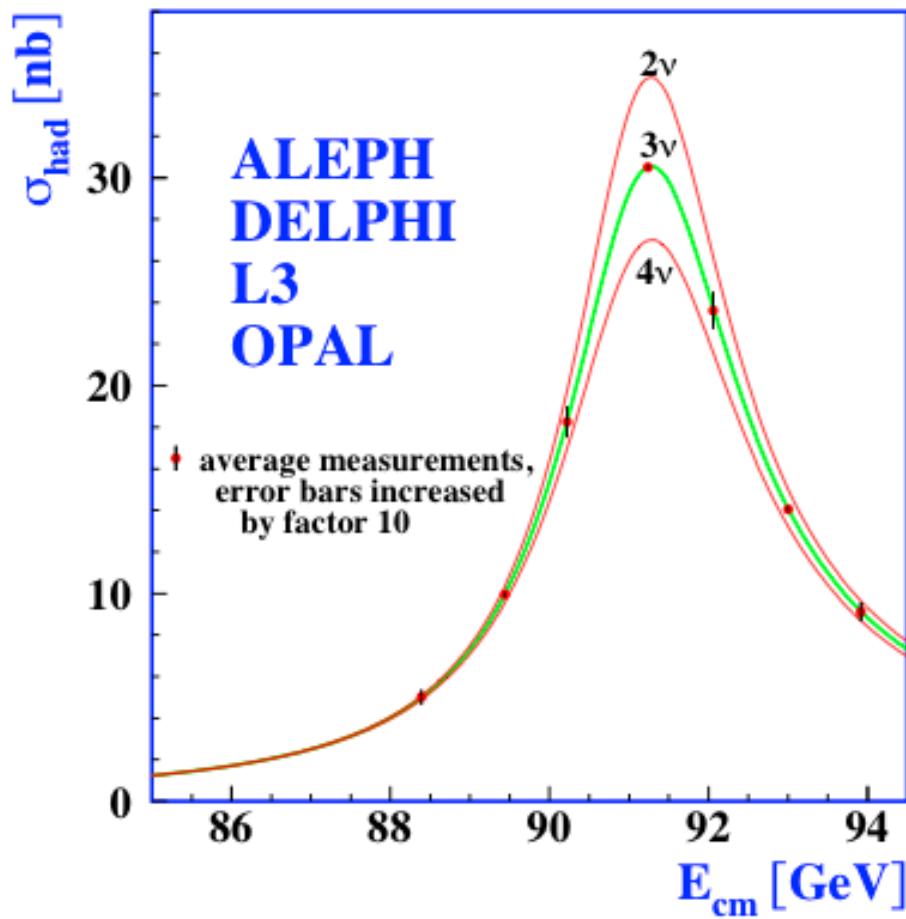
$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_i \sum_j |U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}| \sin^2(1.27\Delta m_{ij}^2 L/E_\nu)$$

As N increases, the formalism gets rapidly more complicated!

N	# Δm_{ij}^2	# θ_{ij}	#CP Phases
2	1	1	0
3	2	3	1
6	5	15	10

Therefore, there needs to be ≥ 3 neutrino mixing for CP Violation!

LEP Experiments at CERN: 3 Active Neutrinos!

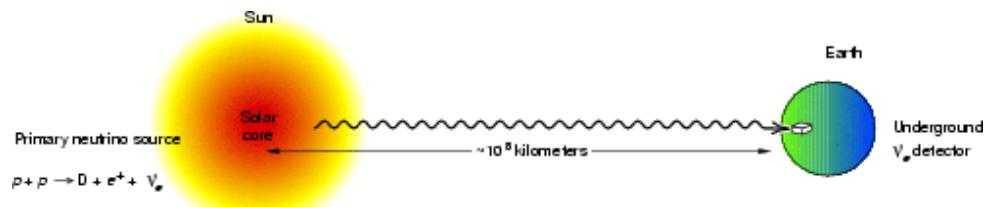


The LEP experiments have measured the number of light, active neutrinos to be 3. Therefore, any additional neutrinos would need to be **sterile**.

Sterile neutrinos would interact by Gravity but not by the Strong, Electromagnetic, or Weak Interactions.

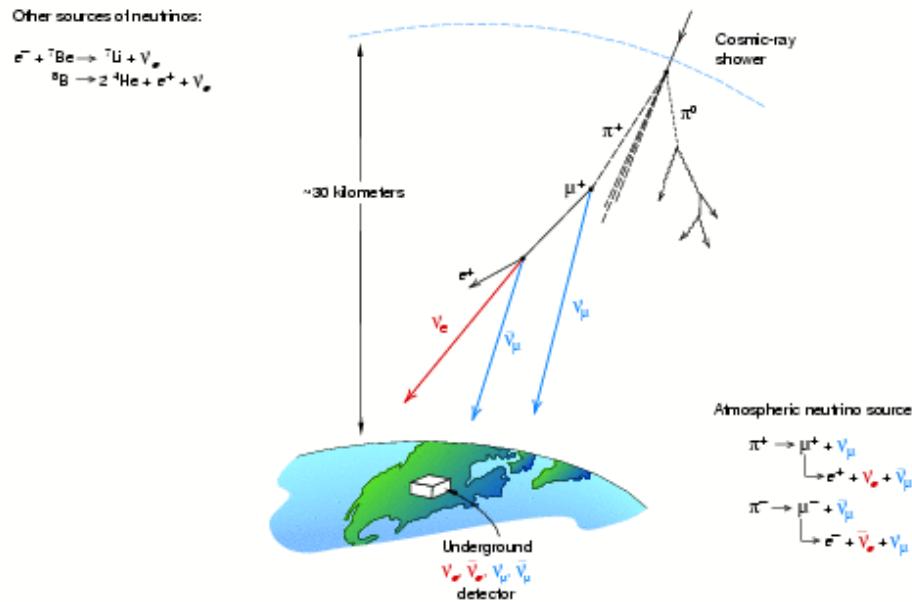
arXiv:hep-ex/0509008v3

Evidence/Observation of ν Oscillations



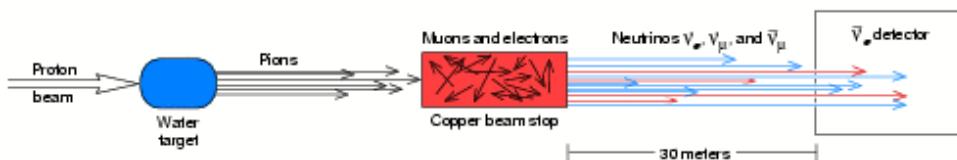
SuperK, SNO, KamLAND

$$\Delta m^2 \sim 0.00007 \text{ eV}^2$$



SuperK, K2K, MINOS, OPERA

$$\Delta m^2 \sim 0.002 \text{ eV}^2$$



LSND, MiniBooNE, Reactor ν

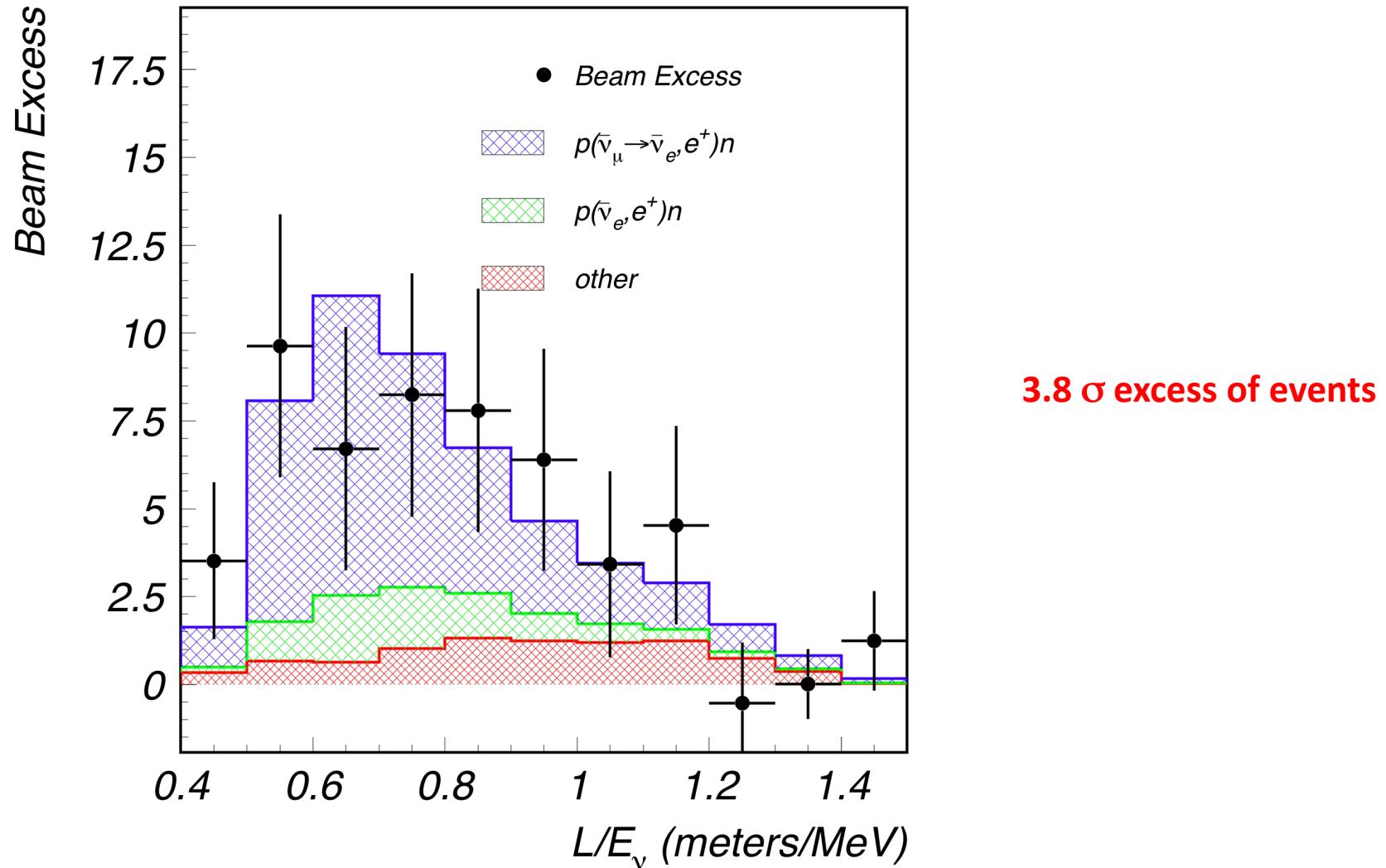
$$\Delta m^2 \sim 1 \text{ eV}^2$$

Tantalizing Results (Anomalies) from Short Baseline ν Experiments Not Explained by 3 ν

- LSND $\bar{\nu}_e$ Excess
- MiniBooNE ν_e Excess
- MiniBooNE $\bar{\nu}_e$ Excess
- Reactor $\bar{\nu}_e$ Anomaly
- Radioactive ν_e Source Anomaly
- These results (2-4 σ) are not directly ruled out by any other experiment.

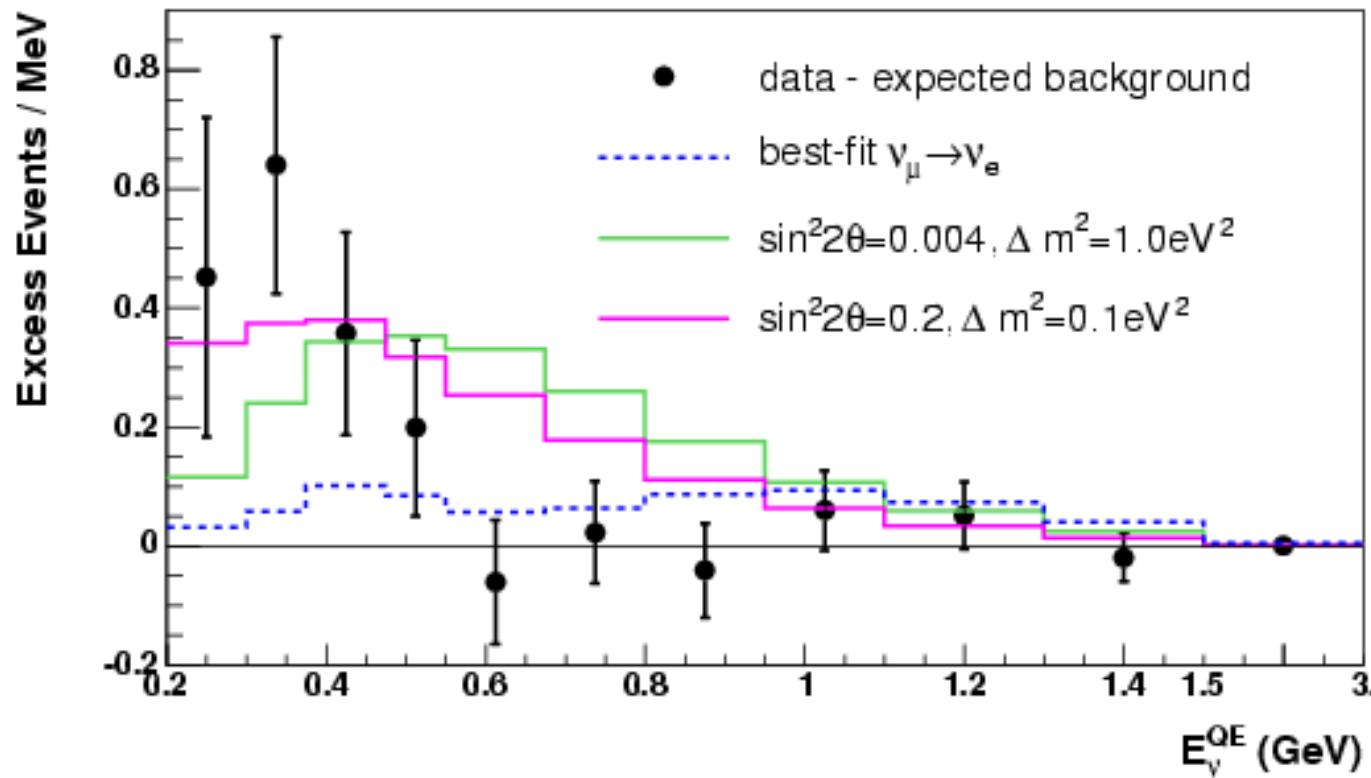
LSND Antineutrino Results

A. Aguilar et al., Phys. Rev. D 64, 112007, (2001)



MiniBooNE Neutrino Results

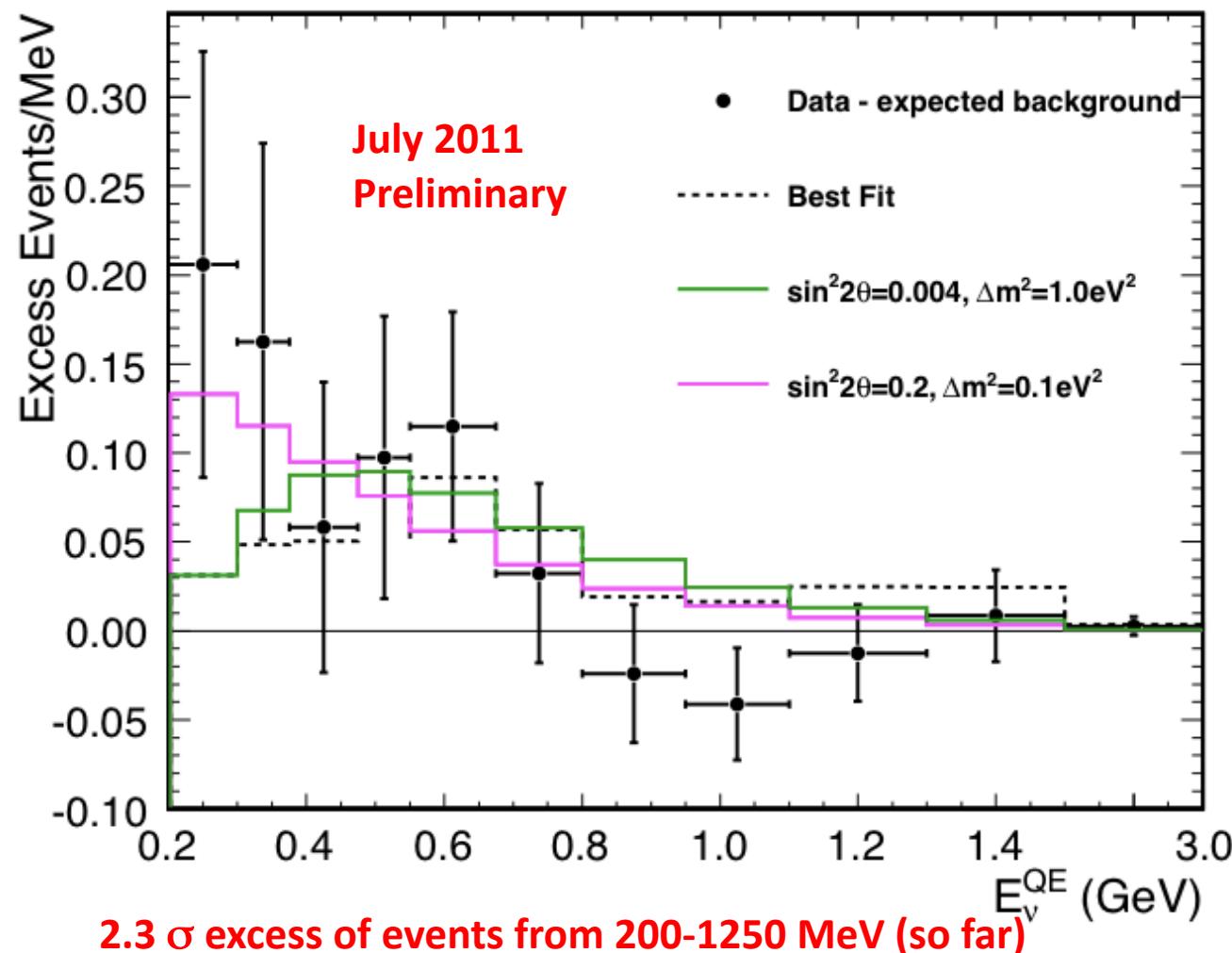
A.A. Aguilar-Arevalo et al., Phys. Rev. Lett. 102, 101802 (2009)



3.0 σ excess of events from 200-1250 MeV

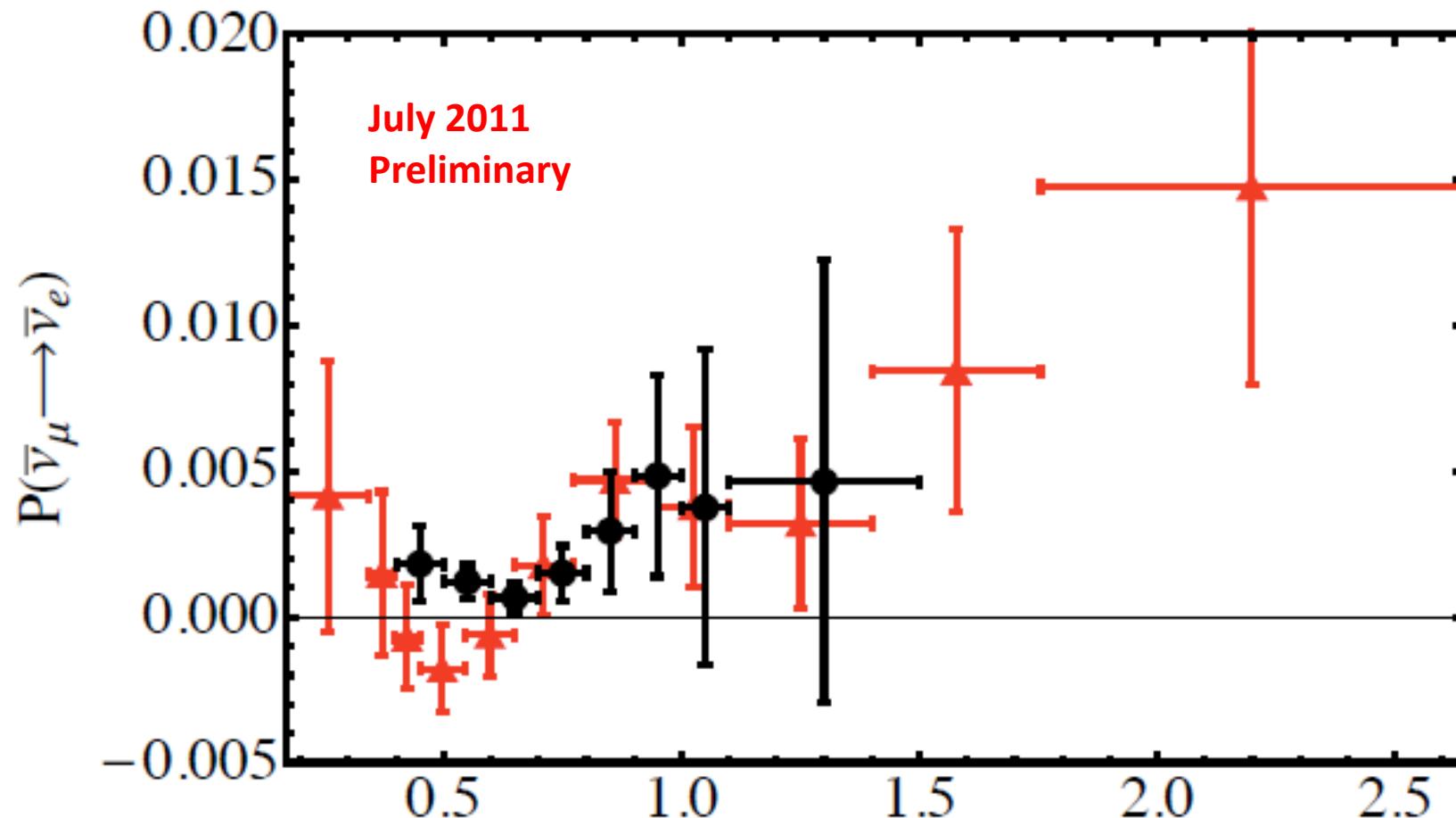
MiniBooNE Antineutrino Results

Updated from A. Aguilar-Arevalo et al., Phys. Rev. Lett. 105, 181801 (2010)



LSND vs MiniBooNE Antineutrino Results

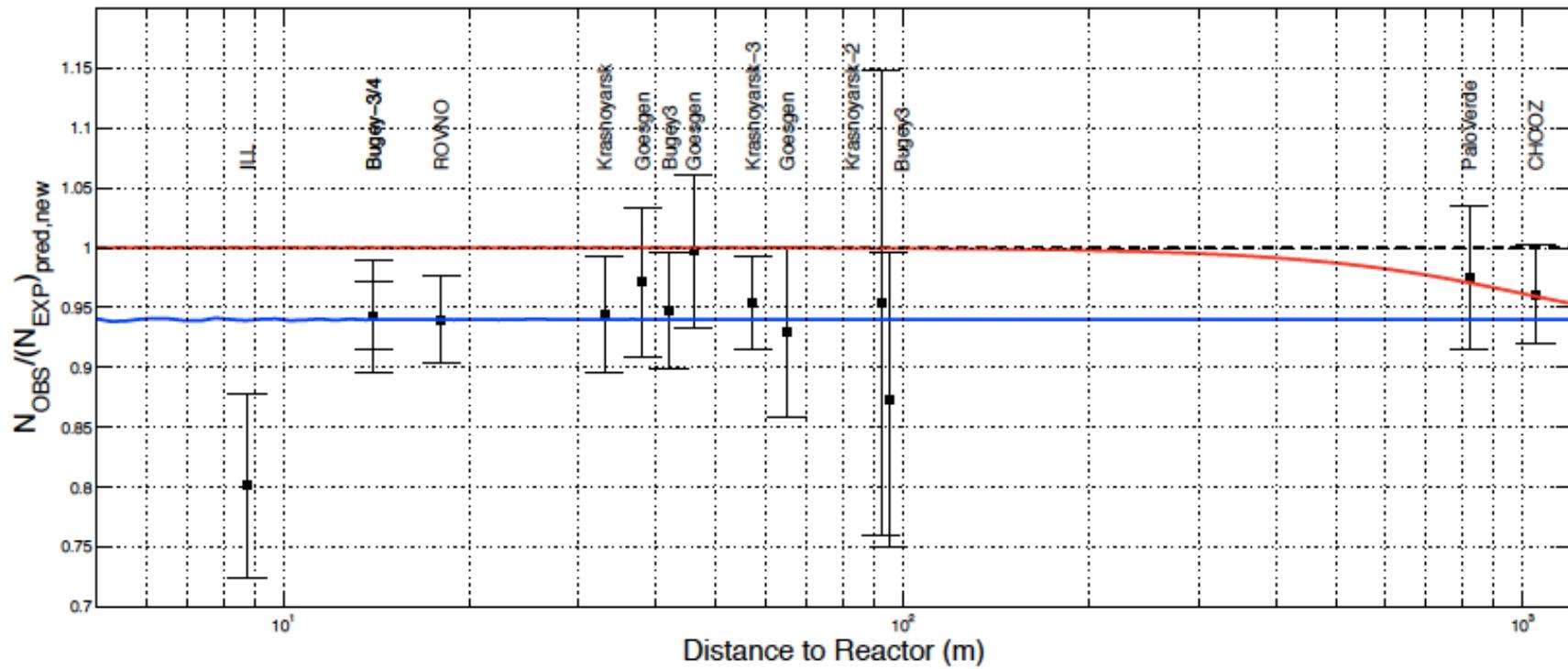
Updated from A. Aguilar-Arevalo et al., Phys. Rev. Lett. 105, 181801 (2010)



$$\frac{L}{E_\nu} \left(\frac{m}{\text{MeV}} \right)$$

Reactor Antineutrino Anomaly

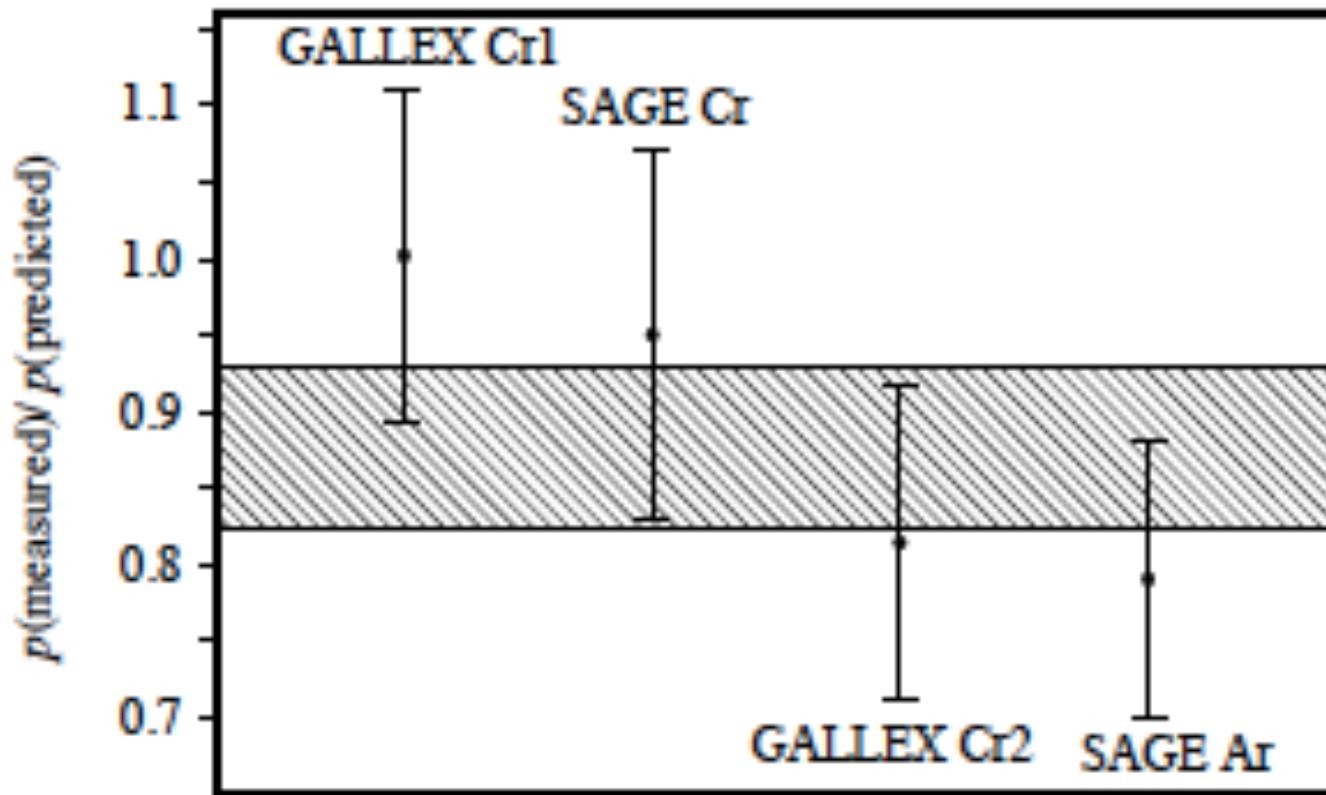
G. Mention et al., Phys.Rev.D83:073006,2011



$$R=0.937+0.027$$

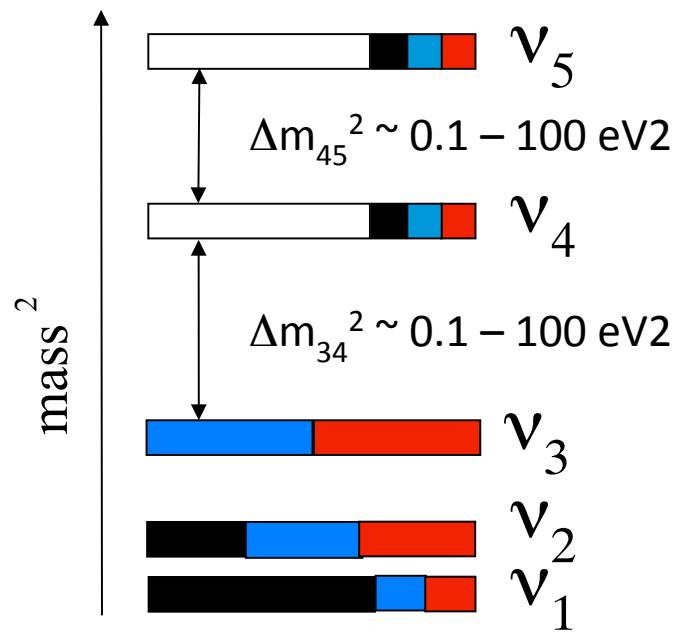
Radioactive Neutrino Source Anomaly

SAGE, Phys. Rev. C 73 (2006) 045805



$$R=0.86\pm 0.05$$

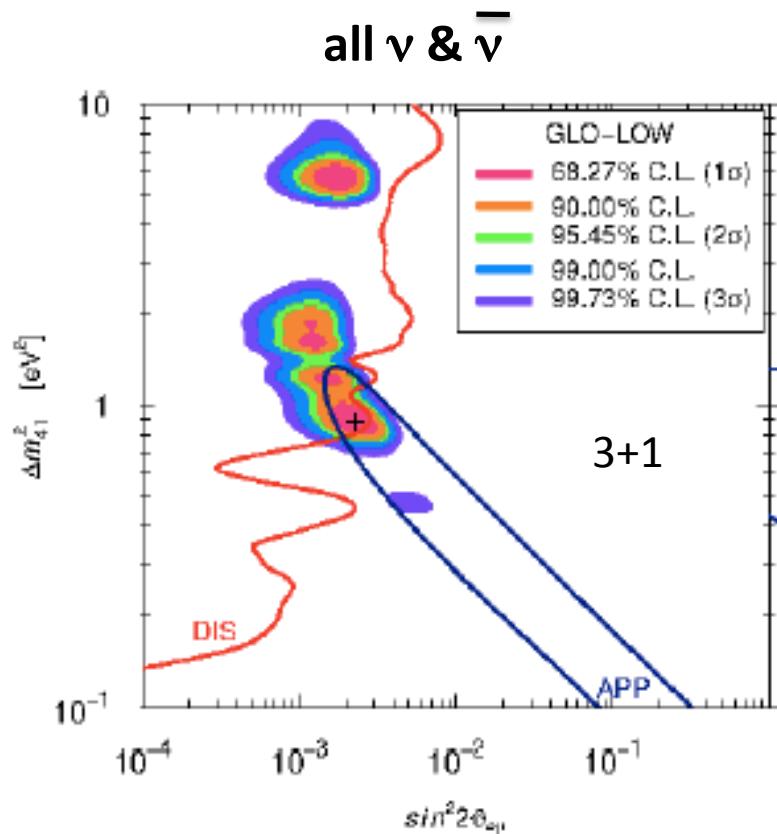
Sterile Neutrinos



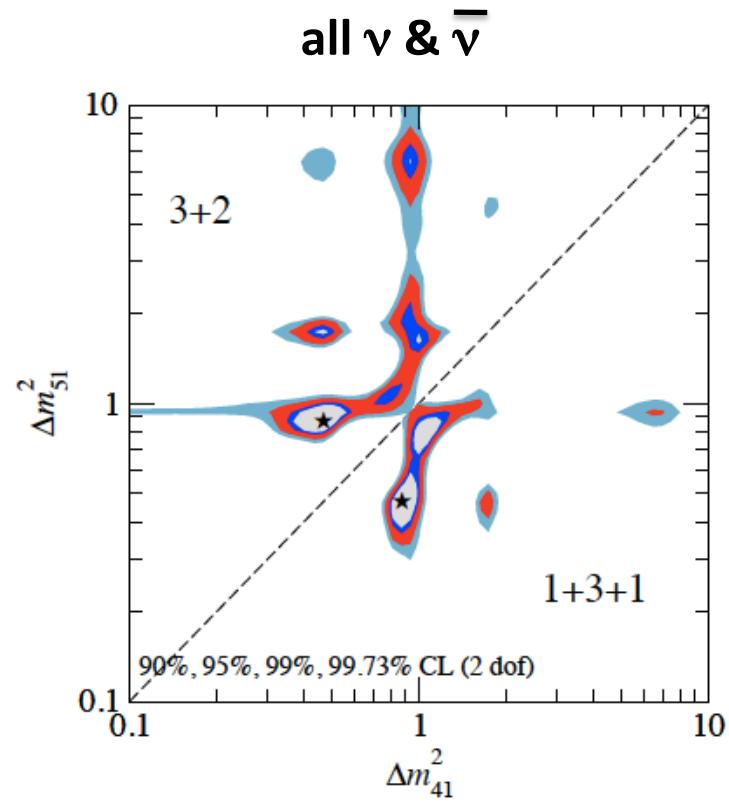
- 3+N models
- N>1 allows CP violation for short baseline experiments
 - $\nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

3+N Global Fits to World ν Data

(Predict observable ν_μ disappearance)



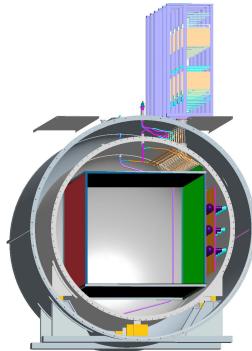
Giunti & Laveder, arXiv:1111.1069
 (Some tension with ν_μ disappearance)
 $\chi^2 = 152.4/144$ DF (Prob = 30%)



Kopp, Maltoni, & Schwetz,
 Phys. Rev. Lett. 107, 091801 (2011)
 $\chi^2 = 110.1/130$ DF (Prob = 90%)

Future ν Experiments

- There is a diverse set of experiments, spanning vastly different energy scales, that have been proposed to test the 3+N models & resolve the present anomalies:
- Accelerator ν Experiments: MicroBooNE, MINOS+, NOvA with two near detectors, NOvA with cyclotron, BooNE (two oil detectors or two LAr detectors), μ storage ring at FNAL, Project X at FNAL, ICARUS at CERN, OscSNS at ORNL
- Reactor ν Experiments: SCRAAM
- Radioactive Source ν Experiments: BOREXINO, Daya Bay, Baksan, LENS
- Atmospheric ν Experiments: IceCube



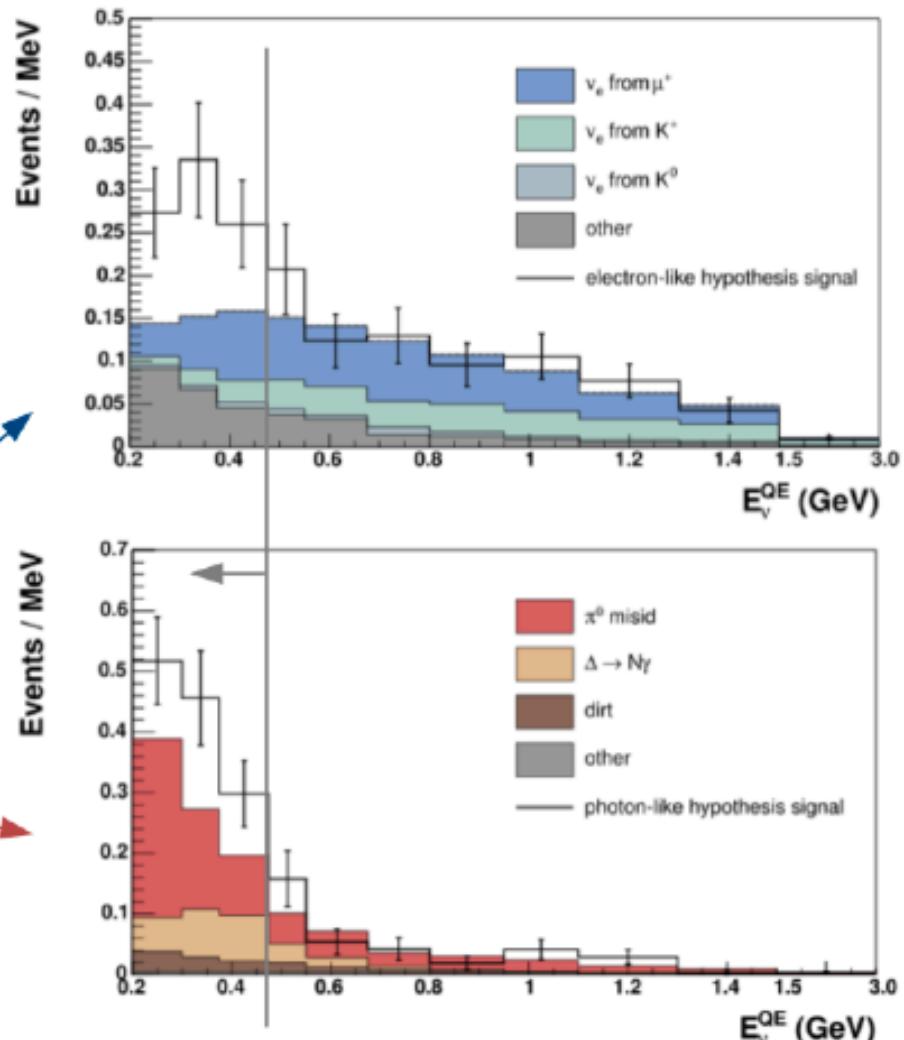
MicroBooNE at FNAL

MicroBooNE sensitivity to low energy excess:

(neutrino running,
70 ton fiducial volume,
x2 higher PID efficiency
than MiniBooNE,
3% mis-ID,
 6.0×10^{20} POT)

Electron-like hypothesis:
36.8 excess events
41.6 background events
5.7 σ stat. significance

Photon-like hypothesis:
36.8 excess events
78.9 background events
4.1 σ stat. significance



ICARUS at the CERN PS

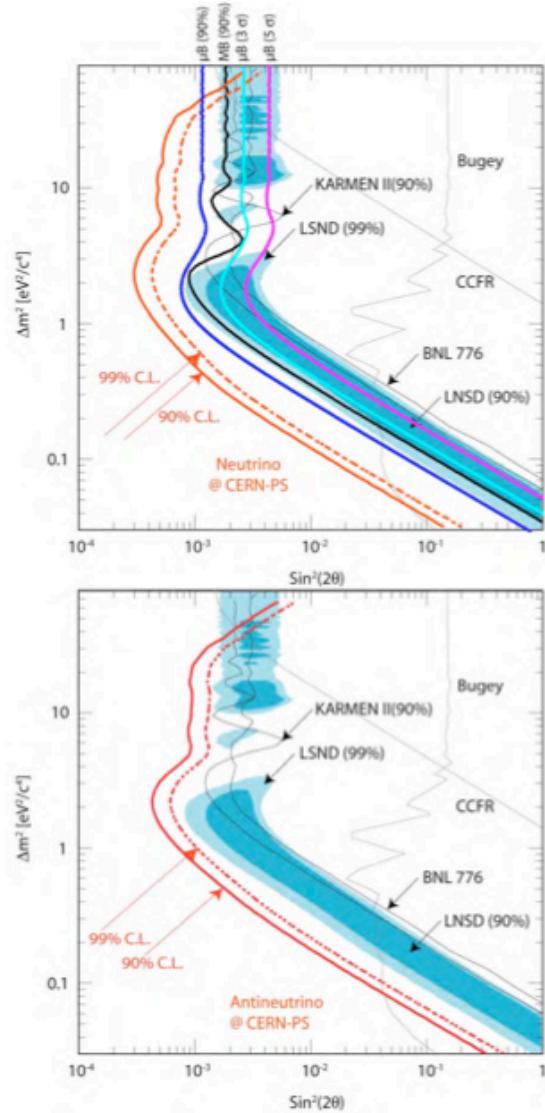


Figure 25. Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (top) and anti-neutrino (bottom) for 2.5×10^{29} pot and 5.0×10^{29} pot respectively. The LSND allowed region is fully explored in both cases.



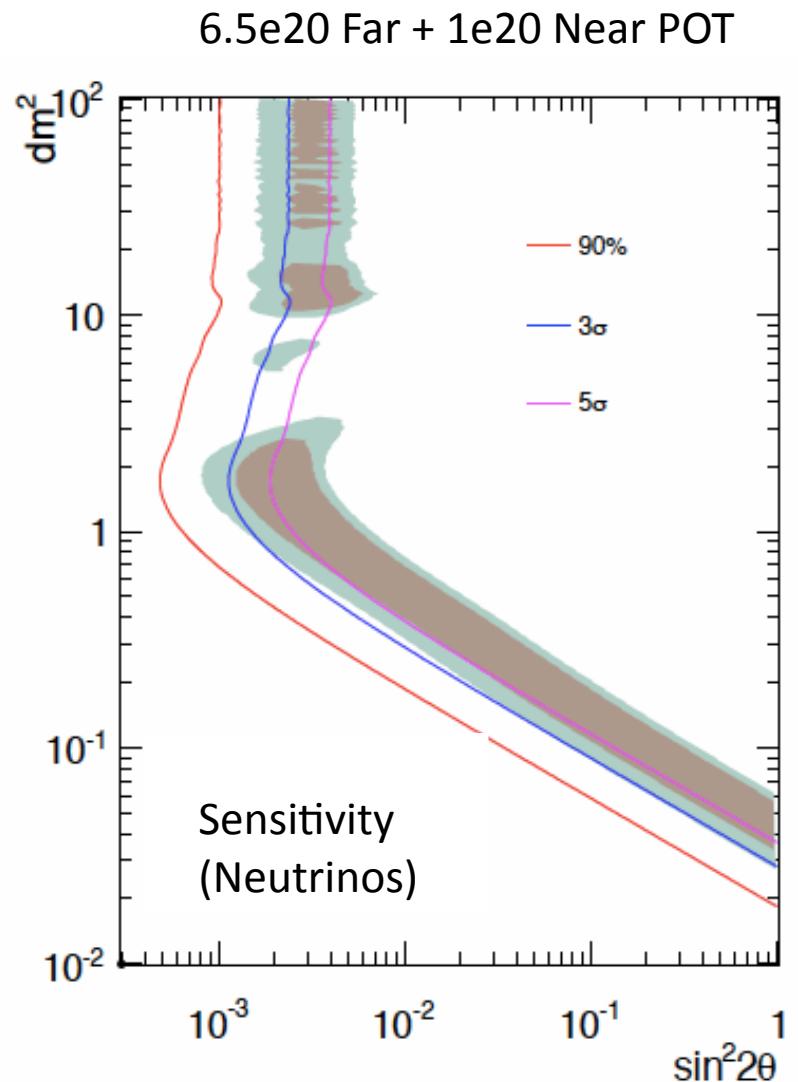
Figure 7. The ICARUS T600 detector installed in Hall B at LNGS.

600 ton ICARUS at 850 m

150 ton LAr at 127 m

BooNE at FNAL

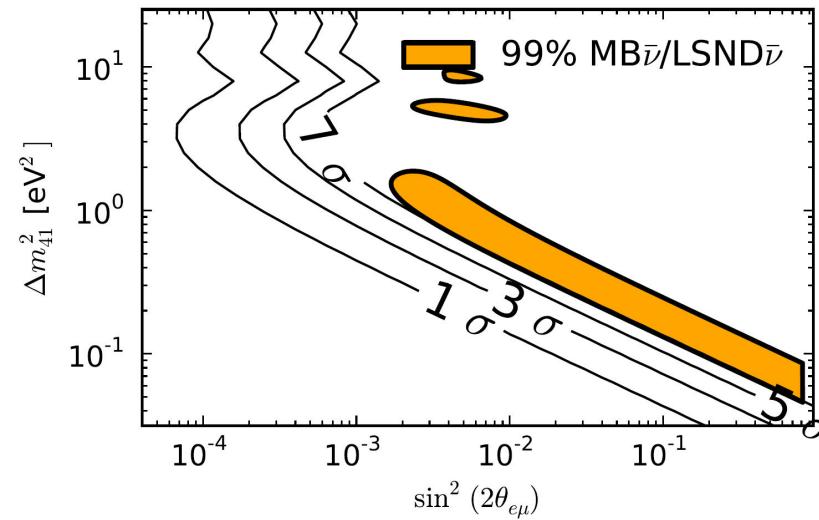
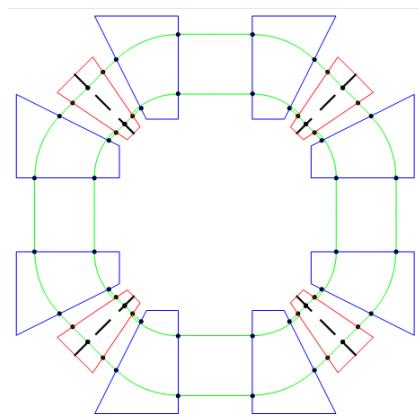
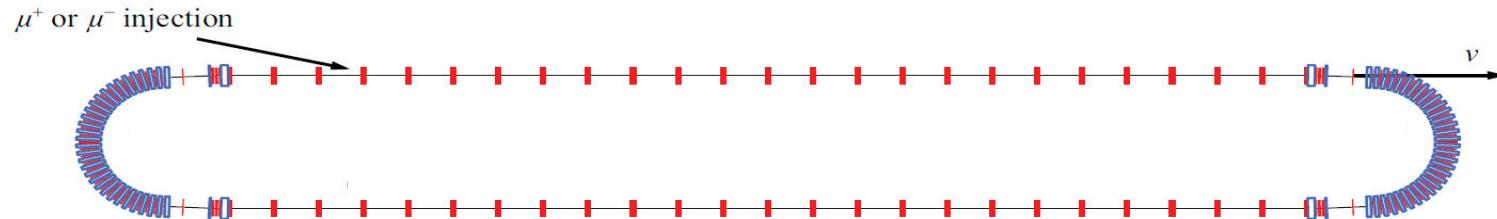
- MiniBooNE like detector at 200m
- Flux, cross section and optical model errors cancel in 200m/500m ratio analysis
- Gain statistics quickly, already have far detector data
- Measure $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance oscillations (& CP violation) and ν_μ disappearance



μ Storage Ring Schematic

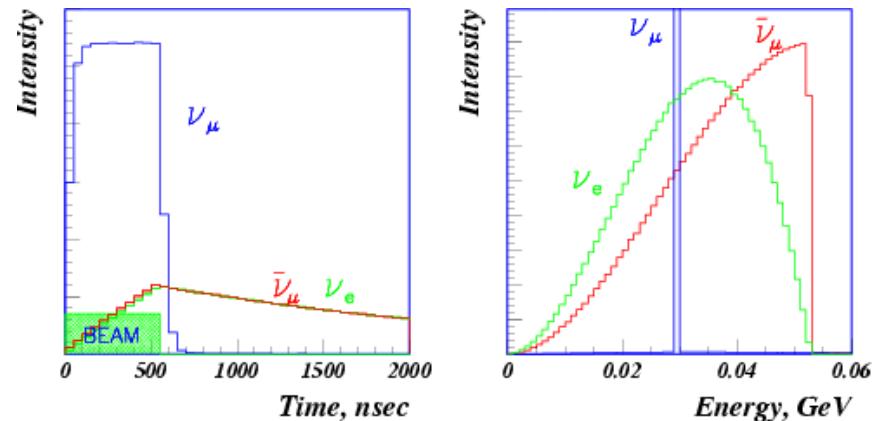
arXiv:1111.6550

- How can we do it?
 - MiniBooNE decay region = 50 m
 - Decay ring with 50 m straight



OscSNS at ORNL

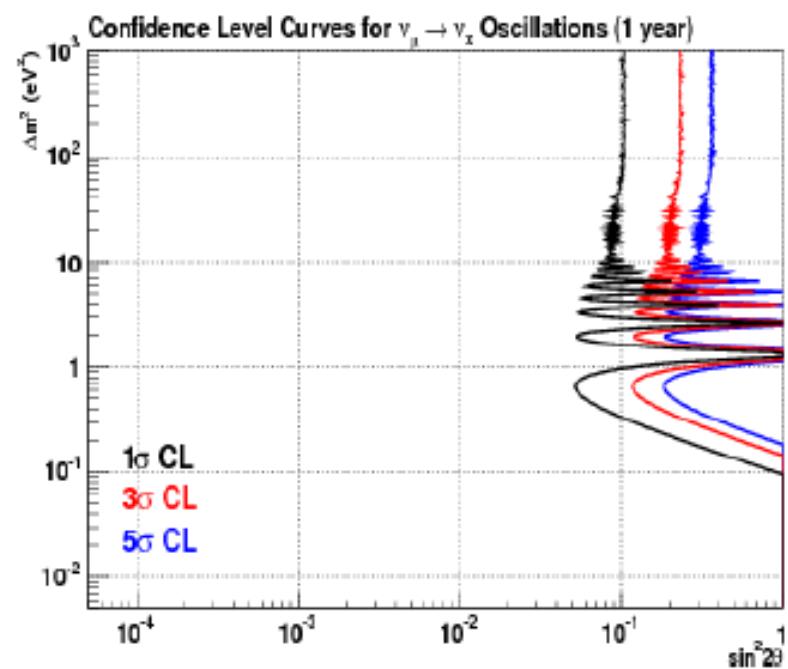
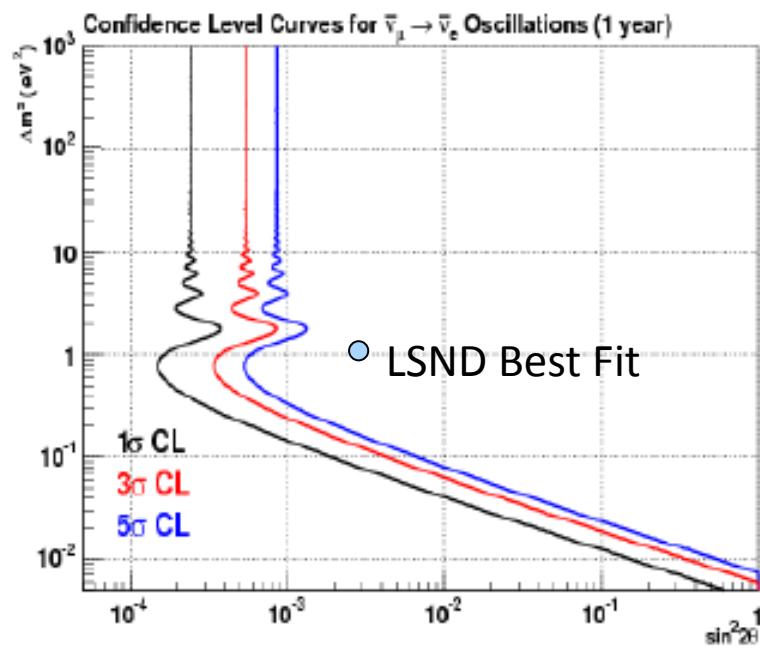
- SNS spallation neutron source
- 1GeV protons @ 1.4MW
- Well understood (and free) flux of neutrinos



OscSNS would be capable of making precision measurements of $\bar{\nu}_e$ appearance & ν_μ disappearance and proving the existence of sterile neutrinos. (see Phys. Rev. D72, 092001 (2005)).

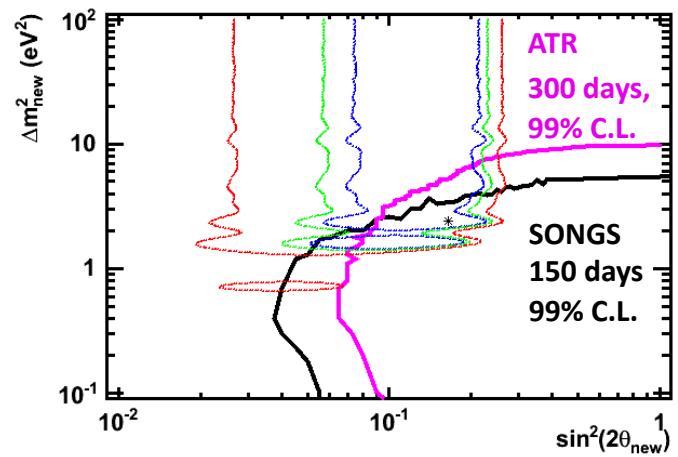
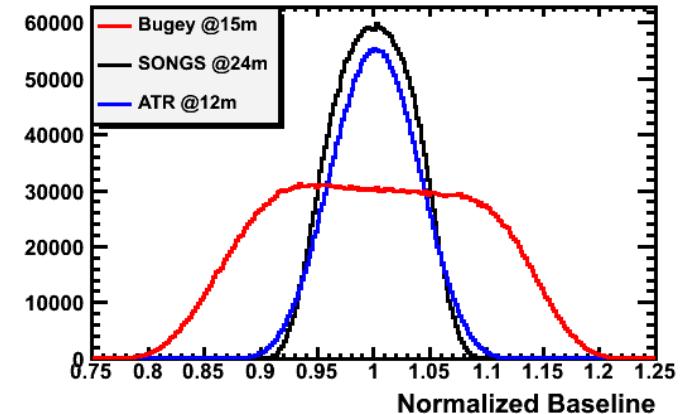
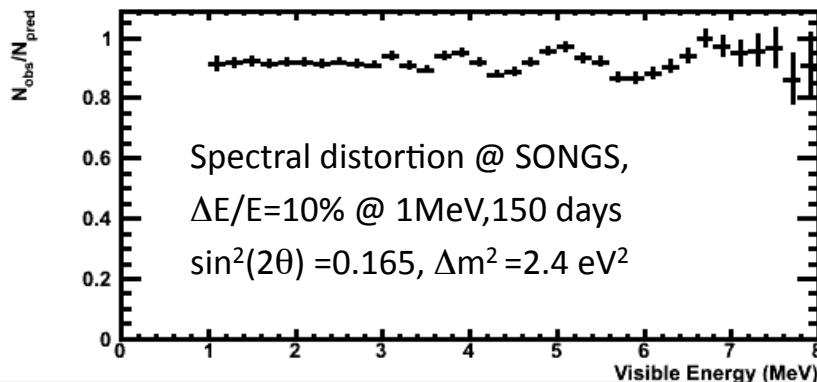
OscSNS at ORNL

- $\bar{\nu}_e$ appearance (left) and ν_μ disappearance sensitivity (right) for 1 year of running (for 60m)



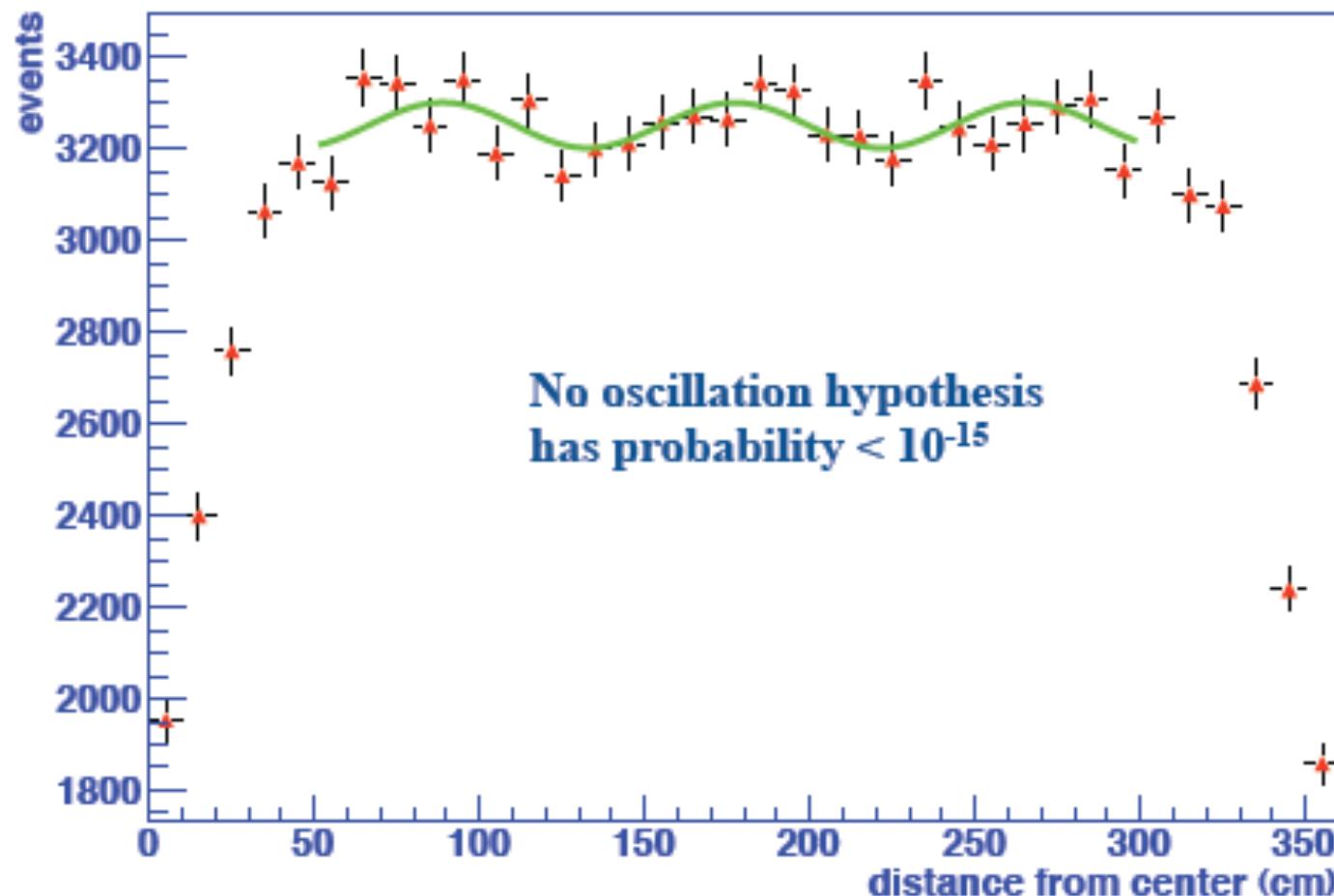
SCRAAM – A reactor experiment to rapidly probe the best fit Reactor Anomaly region

- Past short baseline reactor experiments largely constrain Reactor Anomaly phase space via rate measurements
 - Direct sensitivity to a new oscillation via spectral distortion was limited by large baseline spread, e.g. Bugey3 @15m
- We have identified reactor sites with favorable geometry, overburden, and antineutrino flux for a spectral distortion measurement:
 - SONGS PWR @ 24m baseline (3400 MW_{th})
 - Advanced Test Reactor (ATR) @ 12m (150 MW_{th})
- The SONGS site would allow rapid exclusion of much of the $\Delta m^2 \sim 1\text{eV}^2$ Reactor Anomaly phase space via shape only
- The ATR site would provide cross-check of SONGS at a second baseline and exclusion of larger Δm^2 values



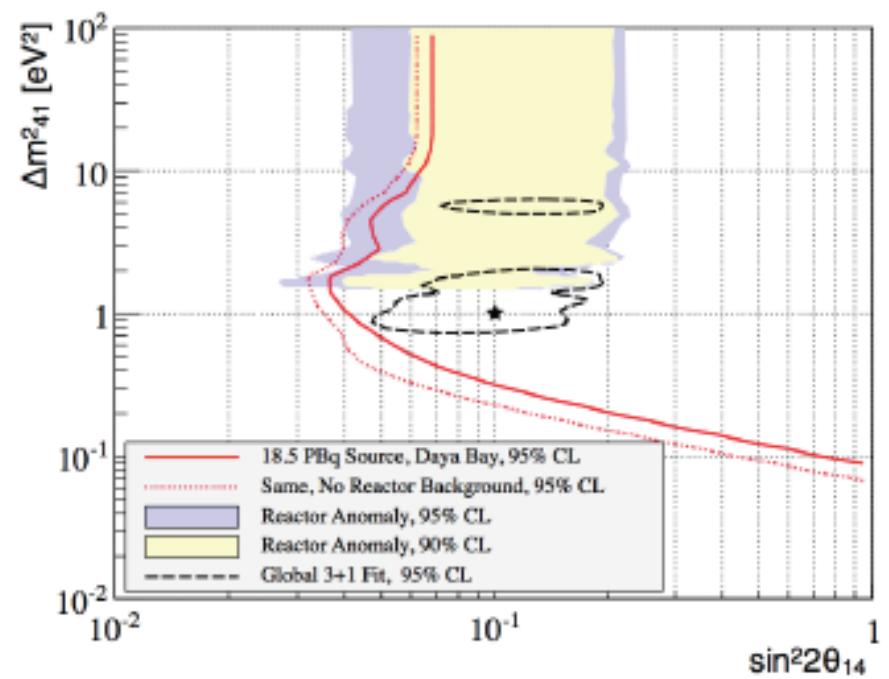
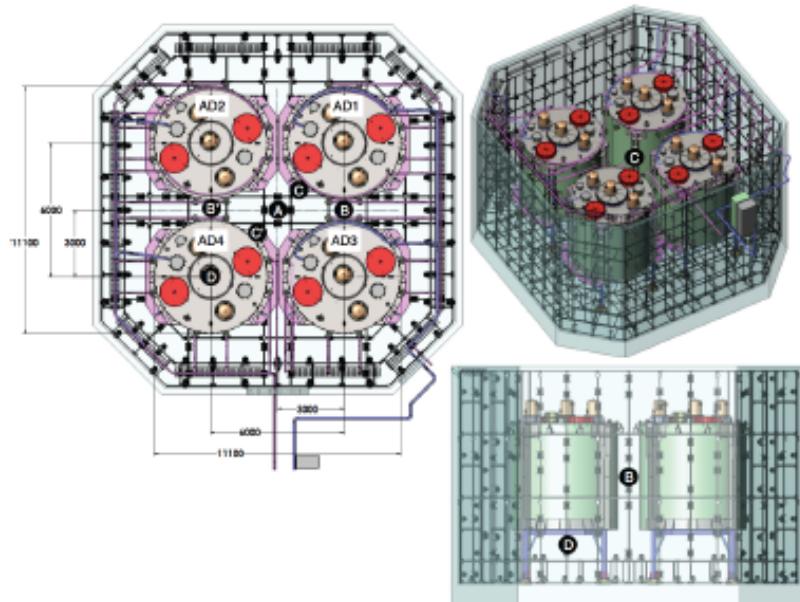
BOREXINO

- 5 MCi ^{51}Cr source in the **center** of Borexino
- 3.3 m F.V. radius
- $\Delta m^2 = 2 \text{ eV}^2$ $\sin^2(2\theta_s) = 0.10$

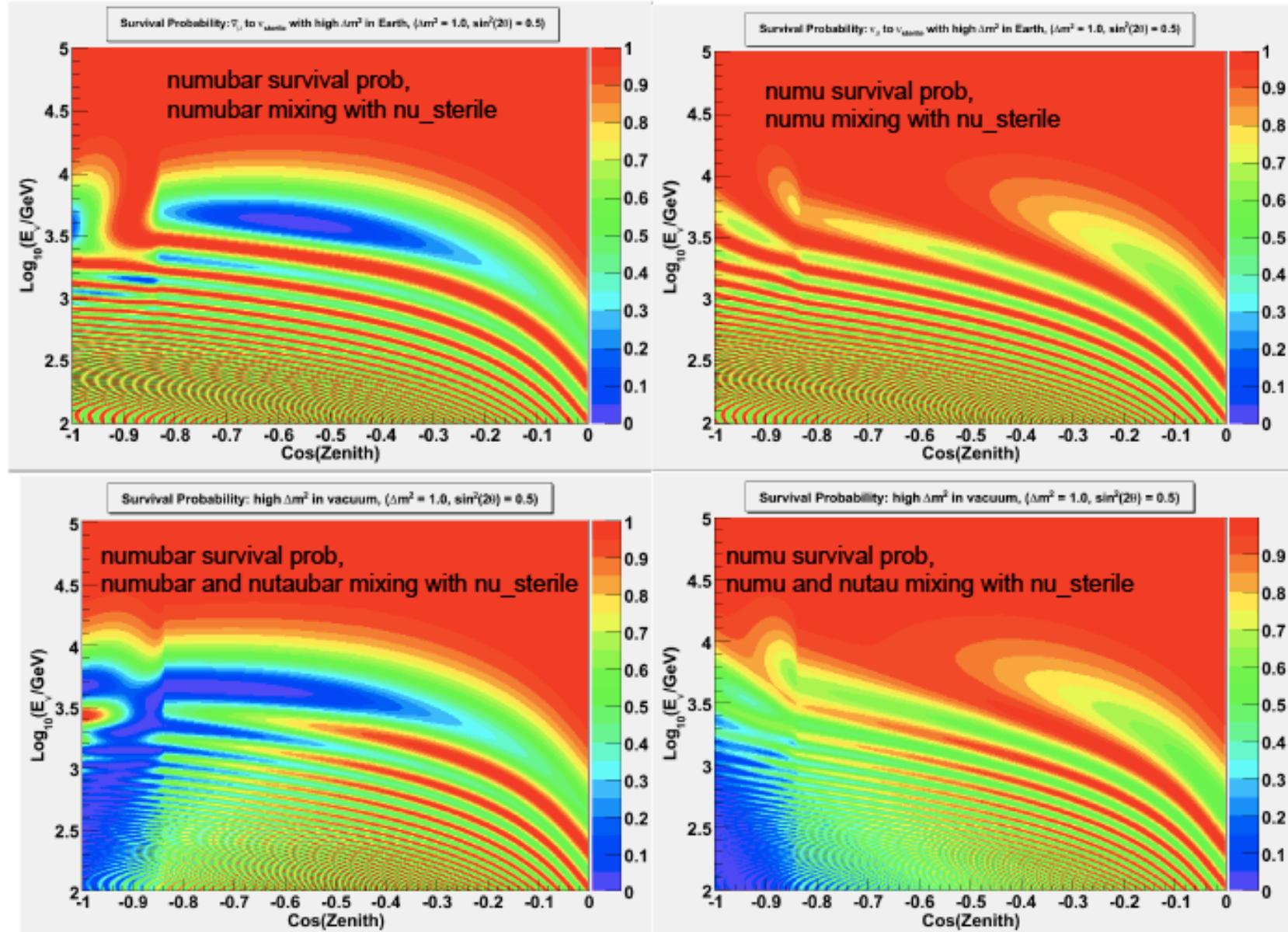


Daya Bay

arXiv:1109.6036



$\bar{\nu}_\mu$ & ν_μ Survival Probability in IceCube for $\Delta m^2 = 1 \text{ eV}^2$, $\sin^2 2\theta = 0.5$



Conclusions

- There are anomalies in short baseline ν experiments that cannot be explained by the 3 ν paradigm and that suggest the existence of sterile ν .
- The world neutrino & antineutrino data can be fit to a 3+1 oscillation model with $\Delta m^2 \sim 1 \text{ eV}^2$, although there is some tension with ν_μ disappearance. This model predicts observable ν_μ disappearance. (Other possibilities include, e.g., sterile ν decay and Lorentz Violation.)
- The world neutrino + antineutrino data fit even better to a 3+2 oscillation model with CP Violation.
- Future short baseline ν experiments (accelerator, reactor, radioactive source, atmospheric) could measure neutrino oscillations with high significance ($>5\sigma$) and prove that sterile neutrinos exist!
- Short baseline oscillations will affect (and are complementary to) long baseline ν experiments and the measurement of θ_{13} and δ (arXiv:1111.4225). (See talks from the SBNW11 & SNAC11 workshops.)

Backup

Neutrino Oscillations

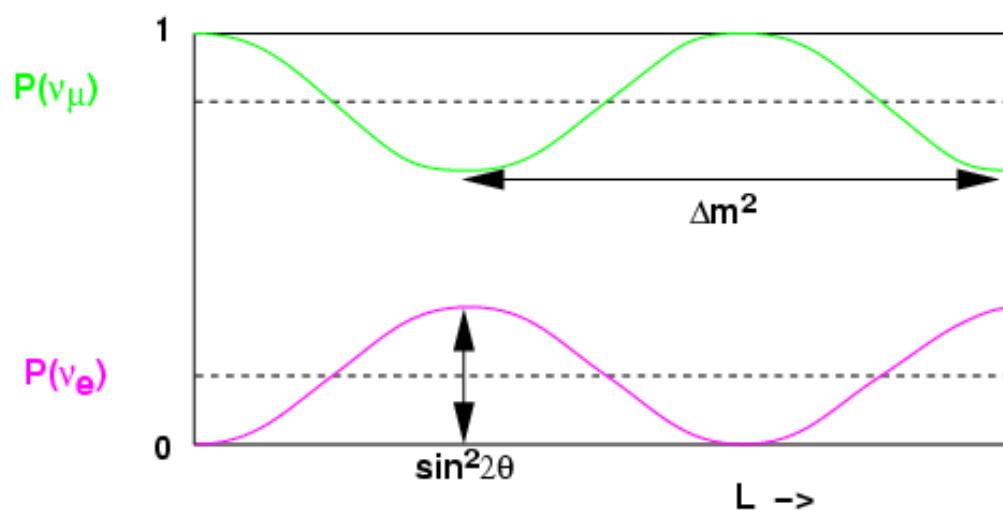
Weak Eigenstates

$$\begin{matrix} v_\mu \\ v_e \end{matrix}$$

=

$$\begin{matrix} \cos\theta v_1 + \sin\theta v_2 \\ -\sin\theta v_1 + \cos\theta v_2 \end{matrix}$$

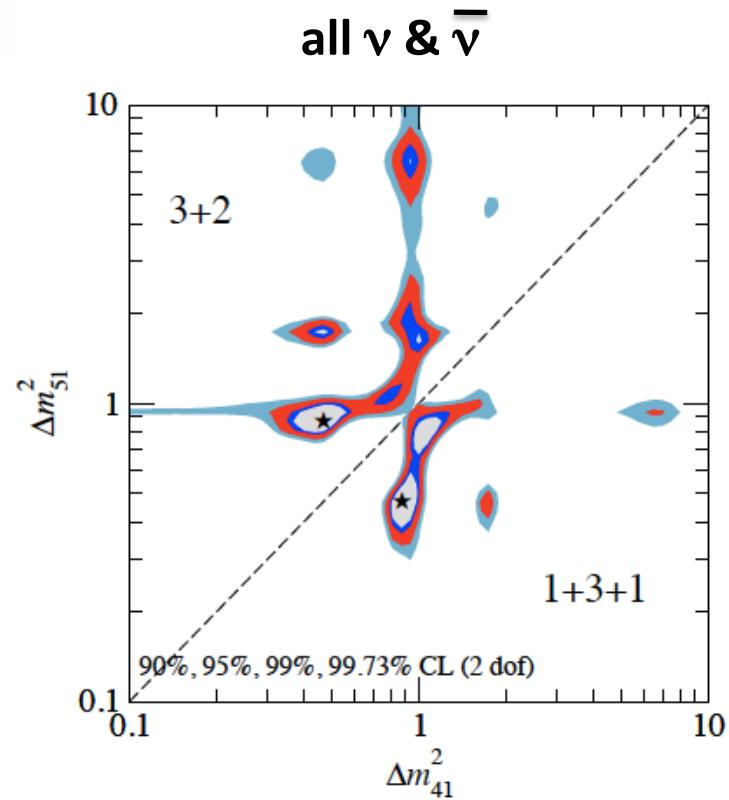
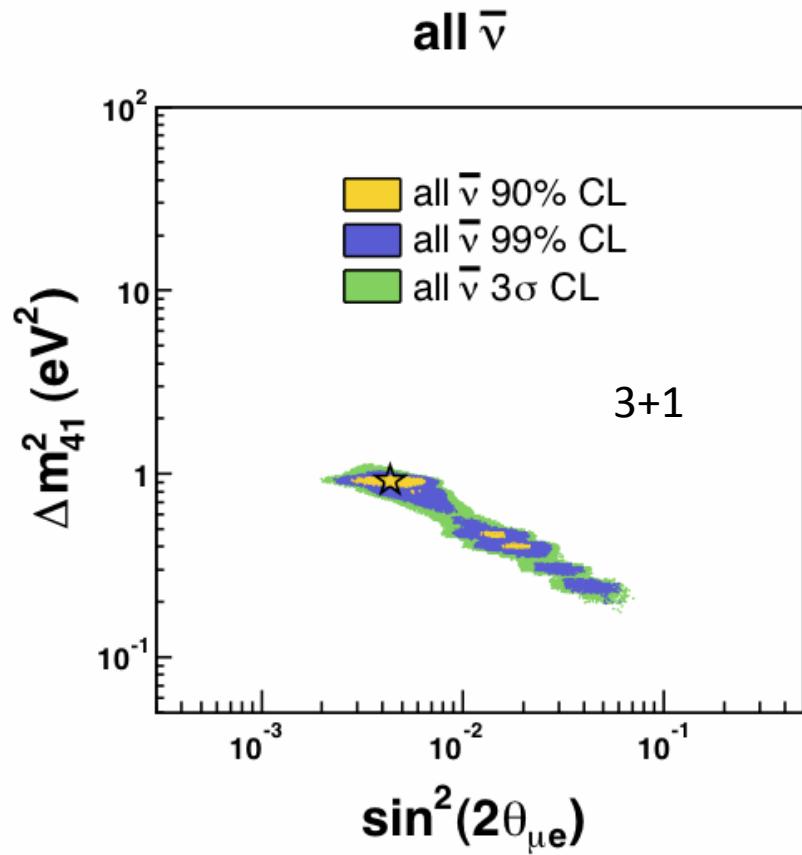
Eigenstates of Propagation



$$P_{v_\mu \rightarrow v_e} = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L / E_\nu)$$

$$\Delta m^2 = m_2^2 - m_1^2 \text{ in eV}^2, \text{ L in meters, } E_\nu \text{ in MeV}$$

3+N Global Fits to World ν Data

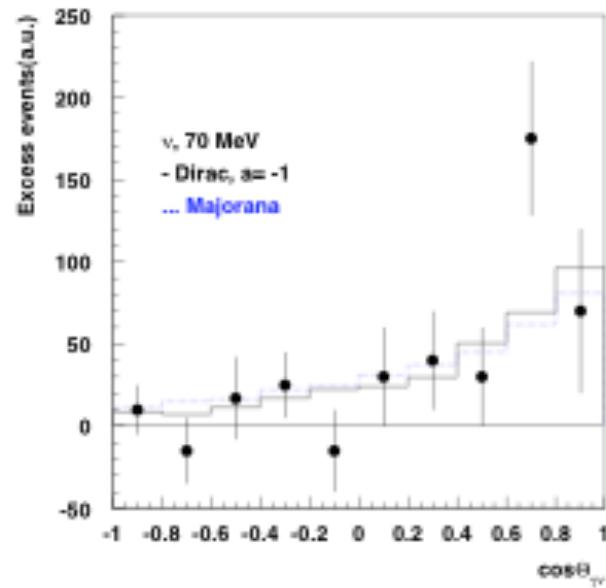
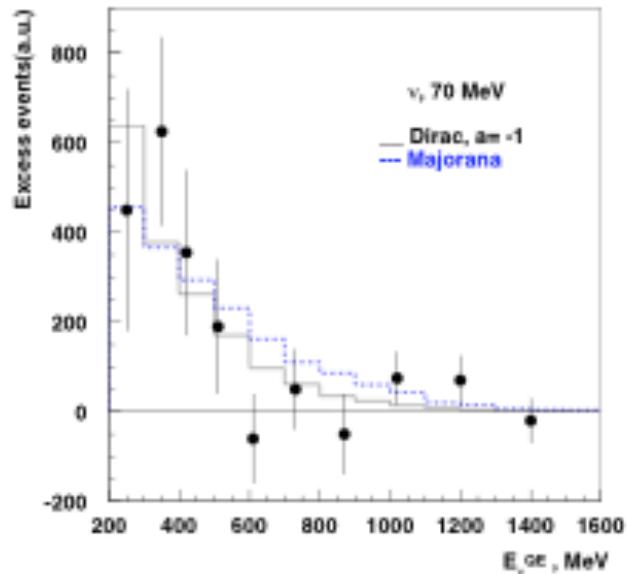
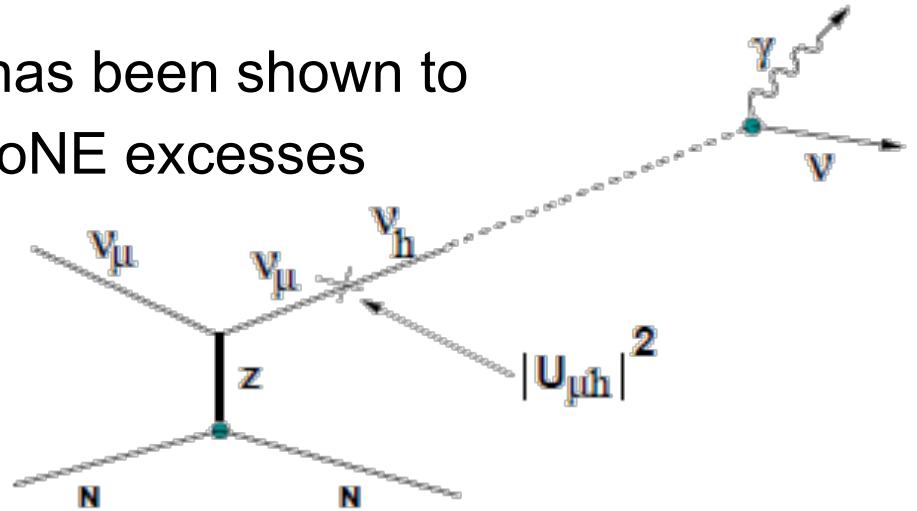


Updated from G. Karagiorgi et al.,
PRD80, 07300 (2009)

Kopp, Maltoni, & Schwetz,
Phys. Rev. Lett. 107, 091801 (2011)

Sterile ν Decay

- The decay of a ~ 50 MeV sterile ν has been shown to accommodate the LSND & MiniBooNE excesses
 - Gninenko, PRL 103, 241802 (2009)
arXiv:1009.5536



Lorentz Violation?

Lorentz- and CPT-violating models for neutrino oscillations

Jorge S. Díaz and V. Alan Kostelecký

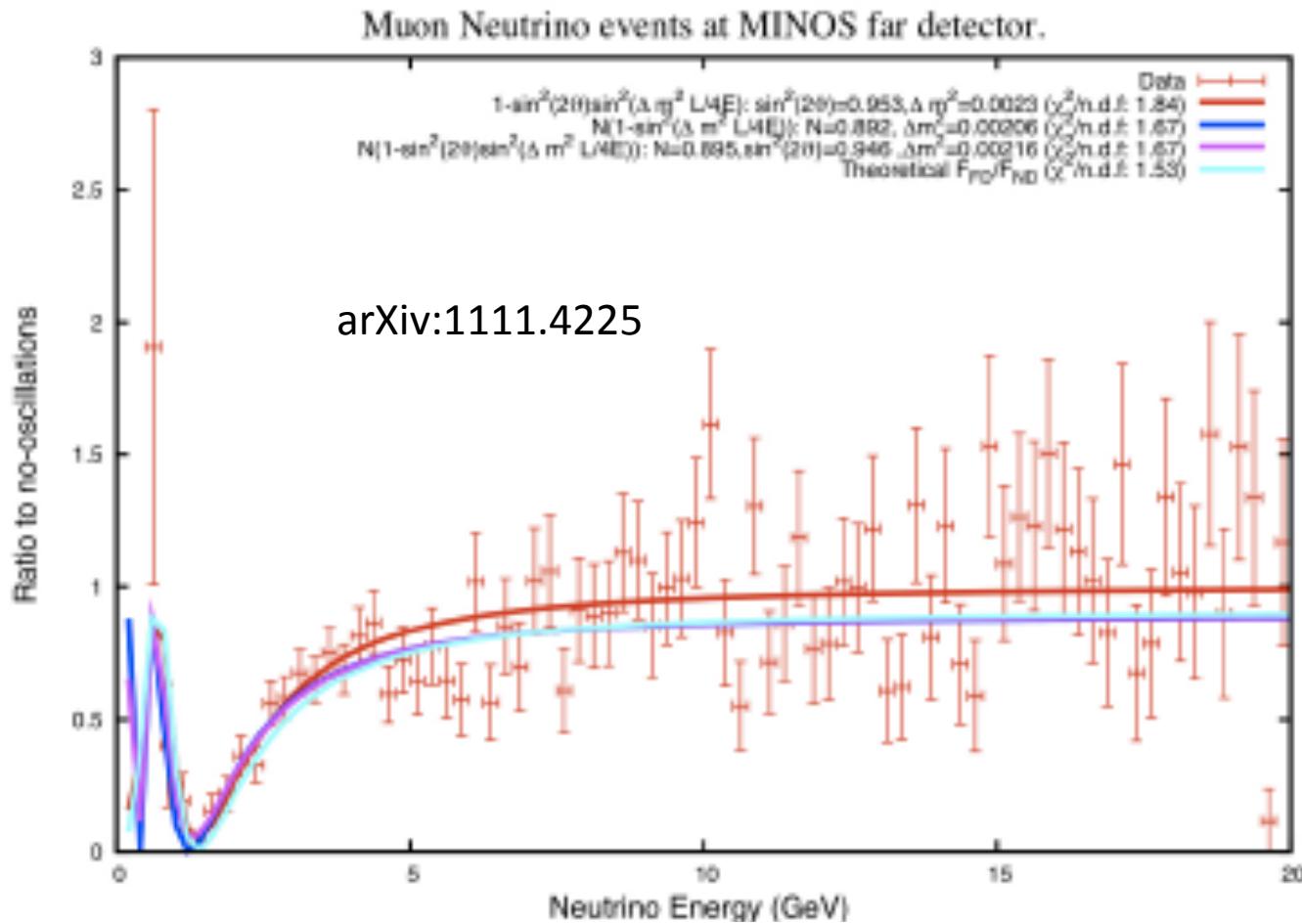
Physics Department, Indiana University, Bloomington, IN 47405, U.S.A.

(Dated: IUHET 561, August 2011)

A class of calculable global models for neutrino oscillations based on Lorentz and CPT violation is presented. One simple example matches established neutrino data from accelerator, atmospheric, reactor, and solar experiments, using only two degrees of freedom instead of the usual five. A third degree of freedom appears in the model, and it naturally generates the MiniBooNE low-energy anomalies. More involved models in this class can also accommodate the LSND anomaly and neutrino-antineutrino differences of the MINOS type. The models predict some striking signals in various ongoing and future experiments.

arXiv: 1108.1799

Fitting MINOS data for ν_μ Disappearance



Case	$\Delta m^2 (10^{-3} \text{eV}^2)$	$\sin^2 2\theta_\mu$	N_μ	$\chi^2/\text{n.d.f}$
I	2.31 ± 0.10	0.953 ± 0.04	1^\dagger	1.65
II	2.07 ± 0.09	1^\dagger	0.895 ± 0.03	1.48
III	2.17 ± 0.13	0.946 ± 0.048	0.897 ± 0.03	1.48
$R_{\mu\mu}$	—	—	—	1.53